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On the radial instability of a homogeneous barrier discharge in nitrogen

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The temporal development of small radial disturbances of the cathode current in a barrier discharge in nitrogen is studied by means of a 2D fluid model. It was found that Townsend discharge mode is stable, whereas in glow mode disturbances of all radii grow with time. Therefore, the domain of discharge homogeneity coincides with that of existence of Townsend discharge. The homogeneity domains are obtained for both linearly increasing and sinusoidal voltages. The filamentation is induced by increase of the voltage growth rate as well as gap width.

1. Introduction

The barrier discharge is a widely used source of non-equilibrium plasma at high pressure. This discharge can be homogeneous even as the reduced gap width *pd* is high (hundreds of Torr cm).

Up to now, different types of the homogeneous barrier discharge are studied experimentally [1-3]. In nitrogen, as the classic equipment (e.g. plane parallel electrodes with glass barriers) is used, only Townsend discharge can be obtained [2,3].

The one-dimensional (1D) simulation of this discharge [4] can succeed in the description of the experimental data, but it is not able to explain the nature of the homogeneity. The 2D modelling [5] reveals different behaviour of radial disturbances in Townsend and glow modes. The growth of fluctuations is a probable way to the filamentation.

This work is devoted to the extensive analysis of the instability of a homogeneous barrier discharge in N_2 relative to radial fluctuations. The homogeneity domains are obtained on the basis of the notions developed.

2. Model

At high pressures and small currents, it is possible to reduce greatly the number of particles responsible for the discharge characteristics and simplify remarkably the kinetics of ionization in N_2 [4]. The effective quenching of excited states, particularly of the metastable state $a'^1\Sigma_u^-$, makes the chemoionization and the stepwise ionization negligibly small. The vibrational temperature in nitrogen is close to room temperature because of the diffusion of vibrationally excited molecules to the barriers. The prevailing type of ions in a homogeneous barrier discharge in nitrogen is N_4^+. This ion is produced in fast conversion processes.

Thus, only the direct ionization is responsible for the discharge maintenance; to describe the discharge, one must calculate only the density of electrons and N_4^+ ions. The calculation is based on the two-dimensional fluid equations coupled with the Poisson equation for the potential. At the barriers, the desorption of electrons ($\nu_{des}=10^4$ s^{-1}) is taken as a source of an initial cathode current.

3. Stability of different discharge modes

To analyse the barrier discharge for the stability, it is necessary to know which qualitatively different modes can exist in the framework of the one-dimensional model. The following discharge parameters are used: gap width L=0.1 cm, dielectric barrier width l=0.01cm (ε=1), surface density of particles at the barriers $\sigma=10^{10}$ cm^{-2}. The phase of active discharge is modelled via the assumption of the linearly increasing voltage. Different discharge modes are obtained by changing the voltage growth rate *dU/dt*.

The electrical characteristics of the discharge in different modes are shown in Fig. 1. At small *dU/dt*, Townsend mode can be observed (Fig. 1a). The cathode current in this mode is amplified in a weakly disturbed electric field. As the voltage growth rate increases (Fig. 1b), damping oscillations of the current occur due to the influence of spatial charge. However, the discharge is also Townsend. More rapid voltage growth (Fig. 1c) changes the discharge behaviour greatly. As U_{gap} attains a certain value, a strong current peak (units of A/cm^2) is observed. In this mode, the field is strongly disturbed by spatial charge.

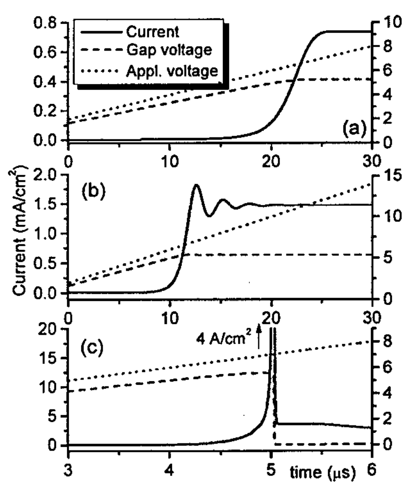

Fig. 1. Different modes of barrier discharge. (a) dU/dt = 2×10^8 V/s, Townsend mode; (b) dU/dt = 4×10^8 V/s, multipeak Townsend mode; (c) dU/dt = 10^9 V/s, space-charge dominated (glow) mode

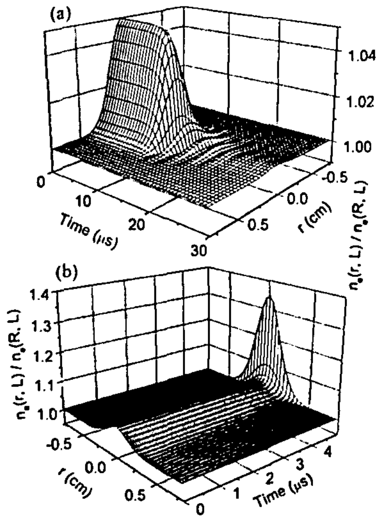

Fig. 2. Evolution of the normalized electron density at the anode in (a) Townsend and (b) glow modes

These modes are analysed for the stability using a small (5%) radial perturbation of the cathode current. The object of study is the electron density at the anode, normalized to that in a non-disturbed discharge.
In both Townsend modes (e.g. Fig. 2a, oscillative mode), the disturbance of the cathode current is strongly damped. Stronger cathode current causes the earlier shielding of the field by surface charge and reduction of the Townsend coefficient in a disturbed domain.
In glow mode, larger spatial charge in a disturbed domain causes earlier formation of an ionization wave (streamer). Therefore, one can see the growth of a disturbance.
The fluctuations of all radii behave similarly. In Townsend discharge they are damped, which testifies its stability. On the contrary, the glow mode is unstable; therefore, in the real discharge it must turn into the filamentary mode immediately.

4. Domains of homogeneity

The immediate consequence from the results of the previous section is that the domain of discharge homogeneity coincides with the domain of existence of Townsend discharge and can be studied via 1D model.
For linearly increasing voltage, the diagram of discharge modes is shown in Fig. 3. It is seen that as the gap width L or the voltage growth rate dU/dt increases, the discharge tends to be filamentary. The decrease of the barrier width reduces the homogeneity domain.
The study of the stability of a discharge at sinusoidal voltage (Fig. 4) allows to take into account the gas heating. This process decreases the domain of homogeneity (Fig. 4, curve B) and improves the agreement with the experiment [2]. At room temperature, the estimation of the boundary of homogeneity by the corresponding dU/dt (solid curve) is successful.

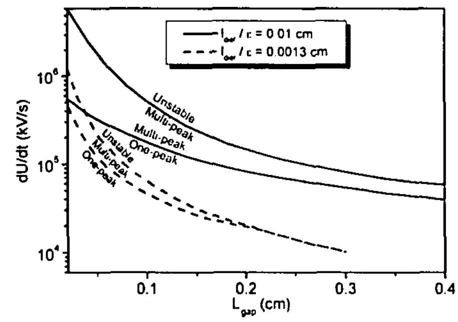

Fig. 3. Diagram of the modes for a barrier discharge at linearly growing external voltage

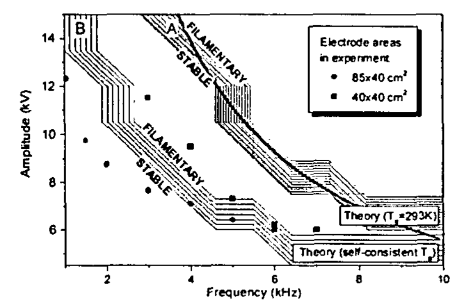

Fig. 4. Diagram of the modes for a barrier discharge at sinusoidal voltage. Dots, experiment [2]; multistroke curves, calculation; solid curve, estimation by *dU/dt*

5. Conclusion

The two-dimensional study shows that the space-charge dominated mode of a barrier discharge in N_2 is unstable and must be filamentary. Only Townsend mode is homogeneous. The calculations of the homogeneity domains are performed; the theory agree well with the experiment as the gas heating is taken into account.

6. Acknowledgements

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